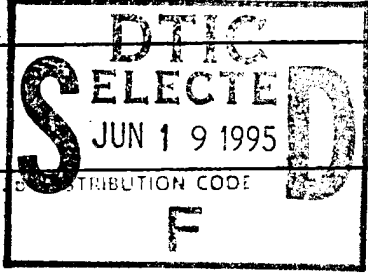


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Read/Write Module for High Capacity Memory Disk

SBIR Phase I

Final Report

April 2, 1995.

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Read/Write Module for High Capacity Memory Disk
Phase I TRP SBIR
Contract No. F49620-94-C-0089

Final Report
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This SBIR program addresses the tracking and alignment sensitivity issues of a practical holographic storage system.

To demonstrate the feasibility of this program, we plan to accomplish the following:

1. Characterize the storage medium.
2. Construct a preliminary tracking system.
3. Study the alignment sensitivity of Fourier transform holograms.
4. Design the final tracking system.

After carefully studying potential markets for the holographic storage system, we have decided to use laser diodes as the light source and photopolymer as the recording medium. The decision was based on cost, size, reliability, availability, and convenience.

We have decided to modify the tracking mechanism of existing optical disk systems and use it for the 3-D holographic disk system. We have procured a CD-ROM and interfaced it to a PC. We plan to create a preliminary recording medium by lamenating a layer of photopolymer onto a CD-ROM disk.

We have partially dissected the CD-ROM. We will obtain tracking signal from the CD-ROM and use it to drive the readout mechanism. (The recording will be performed off-line using another setup.) The readout mechanism is consisted of a laser diode, optics and an output dectector. The tracking signal will be used to rotate the holographic disk to a specified location, to synchronize the firing of the laser diode, and to coordinate the capture of the reconstruction by the detector array.

We have studied the operation principles, the physical specifications, the logical specifications, and the addressing scheme of CD-ROM. We have learned the interface protocol and acquired the control subroutines library. We are developing computer software to monitor the status and to control the movements of the head of the CD-ROM.

We have interfaced a CD-ROM drive to a 286PC. We have also written codes to control some of the needed functions of the CD-ROM drive. The CD-ROM drive has been dissected to allow easy access to its optical components and electronic signals.

We integrated a holographic setup and the CD-ROM drive. A picture of the setup is shown in Figure 1. The holographic setup includes 2 laser diodes (690nm and 780nm), collimating optics, delivery optics, a single-element detector, and a CCD array detector.

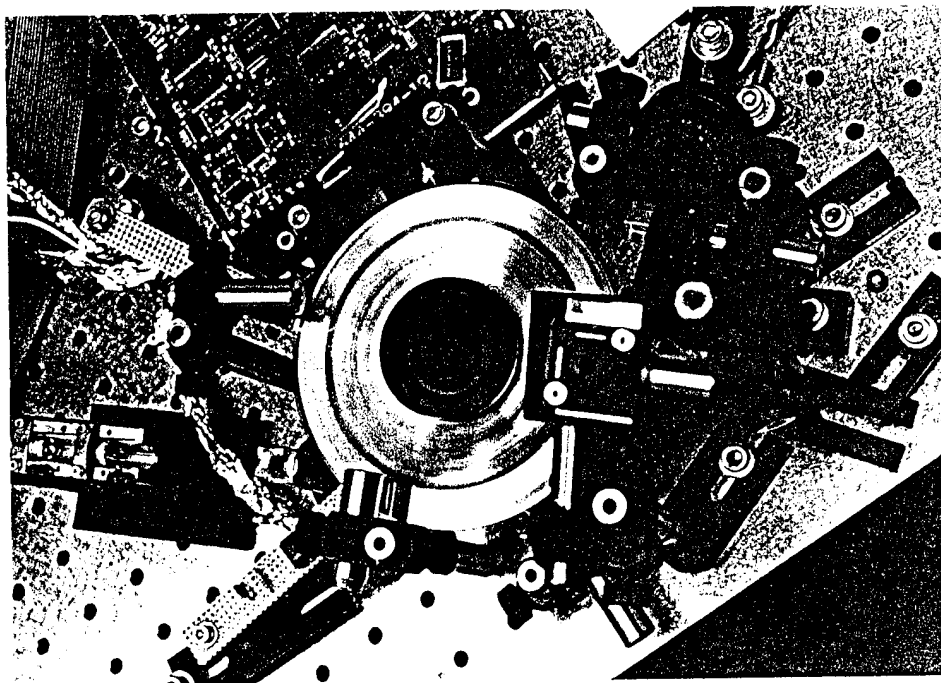


Figure 1. A holographic setup integrated in a CD-ROM drive.

The 690nm, 30mW laser diode, provides power to record and reconstruct holograms. The DuPont photopolymer that we are using is responsive to 690nm. The laser diode will be pulsed during reconstruction. This is required for obtaining a stable reconstruction while the CD-ROM is rotating at high speed. Previous experiments has shown that the laser diode becomes incoherent when the pulse duration is less than $5\mu\text{sec}$. Our calculation shows that reconstructed image movement is excessive if the photon integration time is over $50\mu\text{sec}$. We, therefore, will pulse the laser diode at $10\mu\text{sec}$.

The CD-ROM is used as the substrate for the holographic recording medium. Small holes are drilled on the CD-ROM. Photopolymer films are mounted on the holes. A picture of the recording medium is shown in Figure 2.

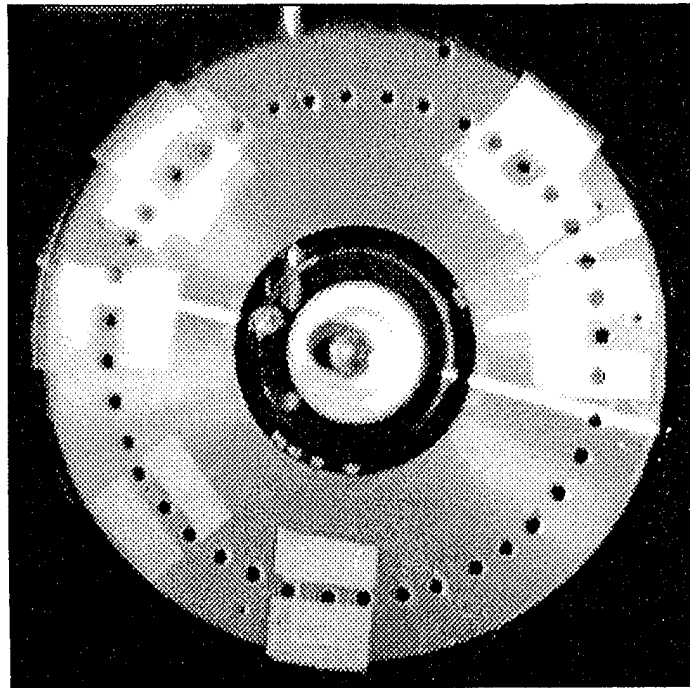


Figure 2. A CD-ROM based holographic recording medium.

The 780nm, 5mW CW laser diode, is used to synchronize the firing of the 690nm laser diode. Since each recording location on the photopolymer is approximately 3mm, high precision location-tracking and firing-synchronization are not needed. This is a significant advantage because the complex tracking mechanism ($\sim 1\mu\text{m}$ resolution) used by most optical memories can be avoided. Currently, we are investigating the precision that is required for tracking and synchronization. Small holes were drilled on the side of the recording medium holes. As the CD-ROM rotates, the synchronization holes move across the path of the 780nm laser beam. A detector on the other side of the CD-ROM detects the transmitted photons. The signal, in turn, drives the firing of the 690nm laser diode. Based on experimental results and the projected location size, we estimate that a precision of $100\mu\text{m}$ is sufficient for tracking and synchronization. For comparison, the precision required is approximately $1\mu\text{m}$.

Preliminary tests show that the integrated drive is working properly. In order to record holograms, the path lengths of the object and reference beams have to be balanced carefully due to the short coherence length of the laser diode.

After we measured a 0.9 fringe visibility in the holographic/CD-ROM setup, we recorded holograms on the photopolymer laminated CD-ROM. We implemented a number of holographic configurations to test their practicalities. The mechanical implementation of the reflection geometry is most convenient. The readout head, which consists of the

angle multiplexing mechanism, the output lens, and the detector array can be all mounted on a common platform. The advantage of such an assembly is that tracking is relatively easy because the spatial relations among components which are used for readout, are fixed. When holograms were recorded in the reflection geometry, the reconstructions were hardly satisfactory. The below-standard reconstructions were caused by the shrinkage of the medium which occurs when it is UV-fixed. The shrinkage is about 3%. A laser diode at a different wavelength can be used for illumination to compensate for the shrinkage effect. The holograms were recorded at 690nm. A 3% decrease in wavelength is equal to -20nm. The laser diode required for compensating the readout is therefore 670nm, a convenient wavelength just by luck.

The objective of experimenting with a CD-ROM setup is to test the adaptability of existing drive mechanism for our hologram storage system. We, therefore, did not employ a 670nm laser diode. Instead, we switch to a transmission geometry for recording holograms. This configuration is less desirable because the angle multiplexing mechanism, and the readout photonics have to be mounted on separate platforms. The reason that we switched is because transmission holograms are very insensitive to medium shrinkage. Holograms were recorded. When the disk was stationary, the reconstructions and the originals were visually indistinguishable.

We recorded holograms in 10 separate locations. The CD-ROM was spinned up to 480 rpm. Any particular hologram can be reconstructed by entering its corresponding address into the controlling PC. When the location moves under the readout head, a laser pulse of 10 μ sec is fired. The reconstruction of the hologram is then captured by a CCD camera. The oscilloscope trace of the firing of the laser diode and its driving signal is shown in Figure 3. A captured reconstruction of a checker-board pattern is shown in Figure 4.

For this phase I program, we have demonstrated that existing optical memory drives can be adapted to be employed by a holographic memory disk system.

Dupont's photopolymer has shown great promises to be the material of choice for the first generation holographic data storage system. It has large dynamic range, high sensitivity, high MTF response, and is UV-fixable. Experiments performed here at Holoplex and at Caltech have demonstrated memories using this material can have high storage density and low probability of error. Although it has a problem of thickness shrinkage, it can be overcome by using clever optical designs such as recording in transmission geometry or readout at a slightly different wavelength. These solutions have been confirmed experimentally. We believe that holographic data storage systems utilizing photopolymer can outperform conventional memories for the same applications by at least one order of magnitude in both density and speed. However, in order to fulfill our ultimate goal of building a practical prototype in 3 years, we have to examine this material critically. We have to create a complete map of its characteristics, evaluate its long term behavior, and measure its performance fluctuations. To do this require a taking a huge amount of data

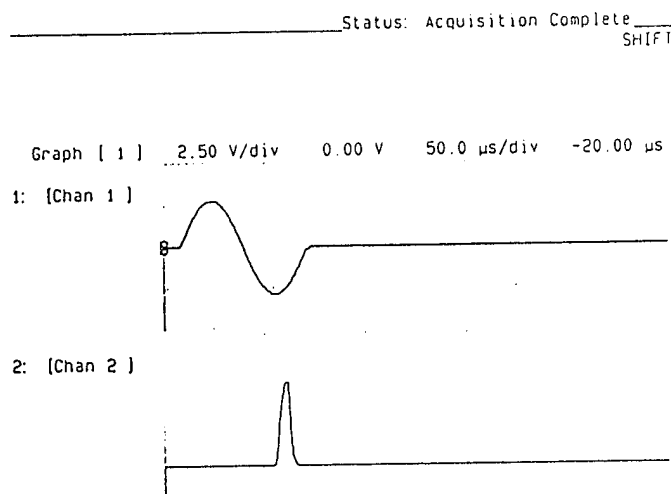


Figure 3. Channel 1 shows the modulating signal that drives the laser diode. It is a truncated sinusoidal wave that is activated automatically when the right location moves under the readout mechanism. Channel 2 shows the optical output of the laser diode. The pulse width is about $10\mu\text{sec}$. The peak power is about 3mW .

over a long period of time. We, therefore, plan to start a 1-year project to accomplish this essential task.

Since much of this task is highly repetitive, it is best to employ an automated system to take data. We have designed and built an automatic system to perform the task (see picture). The material characterization system is controlled by a computer and can run continuously for 10 hours. The setup can be used to measure the dynamic range and exposure curve of the material. To provide a complete mapping of the material characteristics, a number of parameters will be varied. They include: intersection angle between reference and object beams, tilt angle of the grating, modulation depth, total intensity of the recording beams, thickness of the recording medium, type of recording medium, duration between recording pulses, and temperature of post-annealing. In addition, we will also quantify the half-life of recorded holograms, scattering, shelf-life, diffusion of recorded regions, and consistency of the material.

Since many different types of data will be measured, we have designed the system that is easy to reconfigure. Kinematic mounts secured at various strategic positions make interchanging and relocating components trivial. We have also developed a library of sub-

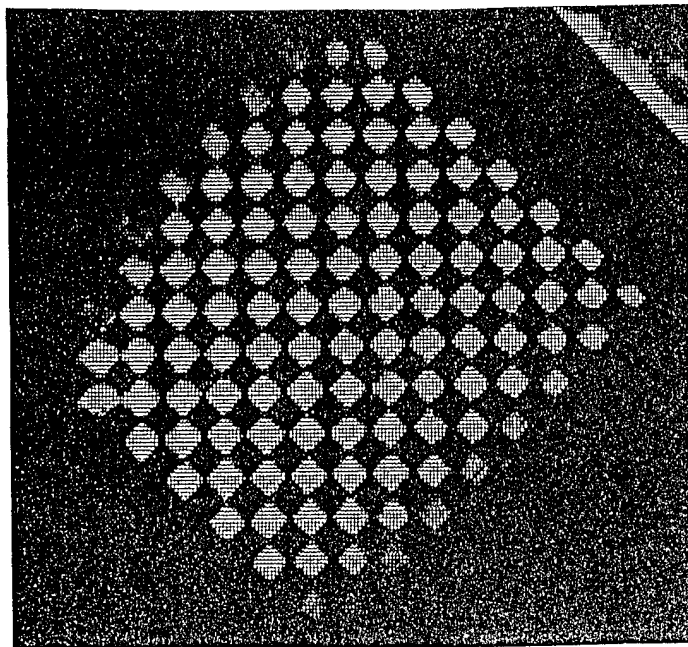


Figure 4. A captured reconstruction of a checker-board pattern when the laser diode is pulsed.

routines to allow easy reconfiguration of the control program. A layered software structure is established. Modifying the control program to run the reconfigured setup is as straightforward as moving the top level commands around. An example of a control program is in the appendix.

We measured the dynamic range of 3 types of photopolymer. The dynamic range is quantified by a figure of merit known as the M -number ($M/\#$). In a setup where M holograms of equal diffraction efficiency sharing a common volume are recorded, the diffraction efficiency η is related to the $M/\#$ by

$$\eta = \left(\frac{M/\#}{M} \right)^2.$$

From a system viewpoint, $M/\#$ is a convenient and useful figure of merit. It not only measures the performance of the recording medium but also the effectiveness of the optical system. Any element that affects the diffraction efficiency is accounted by the $M/\#$. The effects of, for example, the mechanical stability of the optical system, the coherence of the light source, the modulation depth, and the angle between the object and reference beams, are all included. In other words, by measuring the $M/\#$, we bypass the process of analyzing the complex relationship among contributing factors and arrive at the bottom line.

Once the $M/\#$ is known, the diffraction efficiency can be quickly calculated. From the diffraction efficiency, we can determine the storage capacity limit in terms of laser power, signal-to-noise ratio, data transfer rate, exposure time, etc.

Figures 5, 6 and 7 show the results of the $M/\#$ characterization of three different films of DuPont's photopolymer. They are all sensitive to 690nm. The thickness of the film is 20 μm , 40 μm , and 85 μm respectively. In each experiment, 80 holograms were peristrophically multiplexed in an approximately 1 mm diameter spot. The total exposure intensity was 0.5 mW/cm². The exposure time for each hologram was 20 sec. After the holograms were recorded, 30 seconds were elapsed to allow for polymerization to complete. The diffraction efficiency of each hologram was then measured, which is shown by the y-axes on the left. The incremental $M/\#$ was calculated by taking the square root of the diffraction efficiency. The incremental $M/\#$ s were summed to produce the cumulative $M/\#$ s, which are shown by the y-axes on the right. The $M/\#$ of the three films are 1.6, 3, and 6.8 respectively. It appears that the $M/\#$ approximately scales linearly with the thickness. Also note that there is no gain in diffraction efficiency for the first few holograms. That is because the films have to be sensitized.

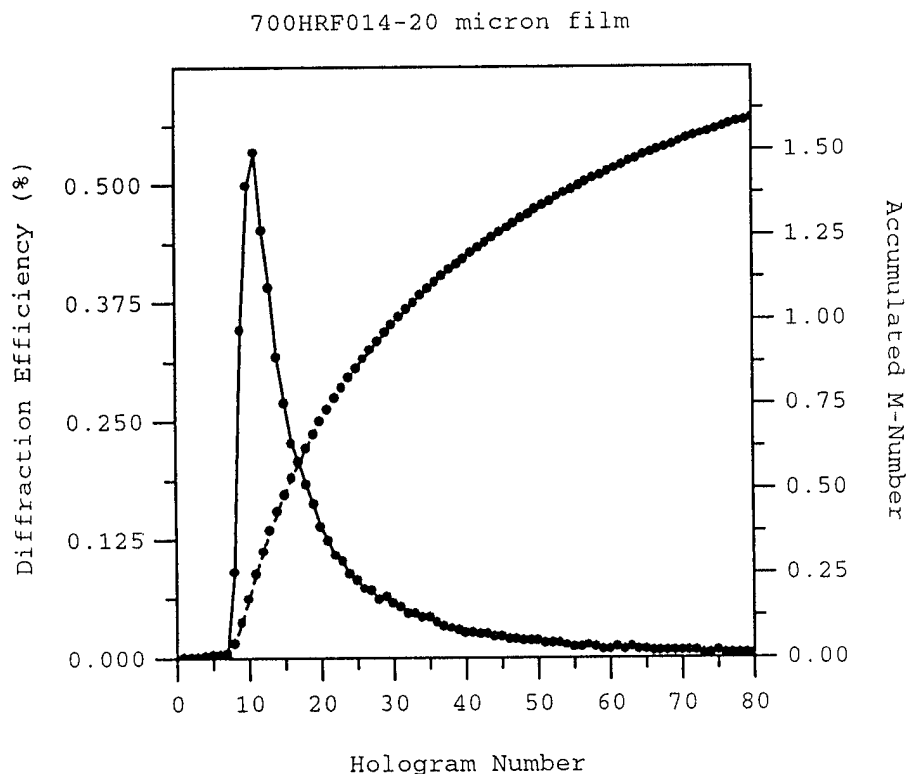
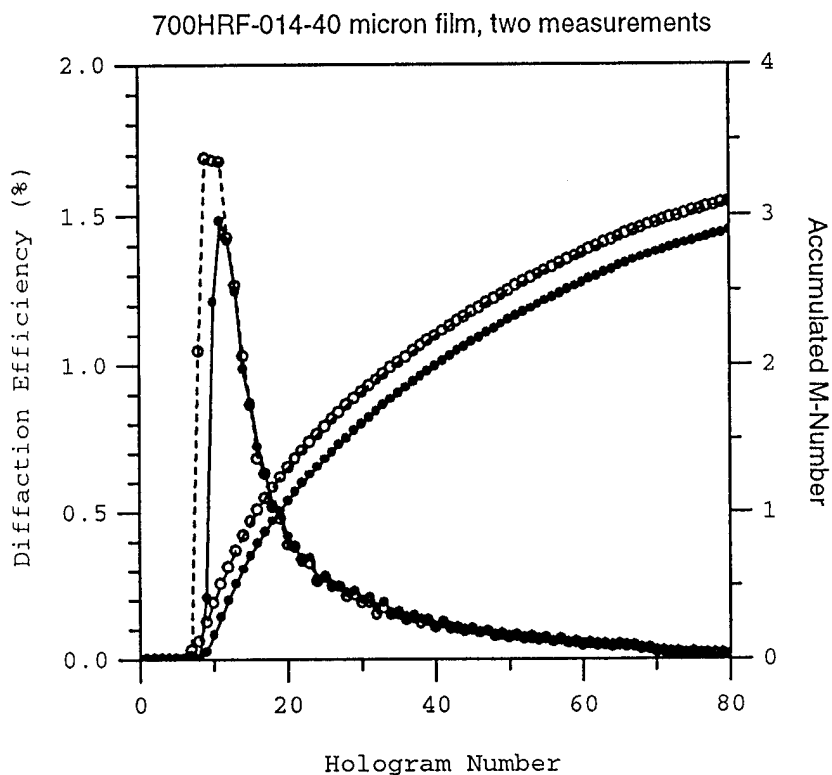


Figure 5. $M/\#$ characterization of a 20 μm thick film.



In the phase I proposal, we proposed to accomplish tracking and alignment of holograms through the use of holographic gratings embossed on the disk substrate. While technologically feasible, this tracking method imposes additional costs to the overall system due to the embossing and the alignment of the disks. If the tracking and alignment markers can be embedded in the data stored, savings in cost, and a simpler tracking mechanism will result. We have designed such a system and the details are submitted as part of the phase II proposal.

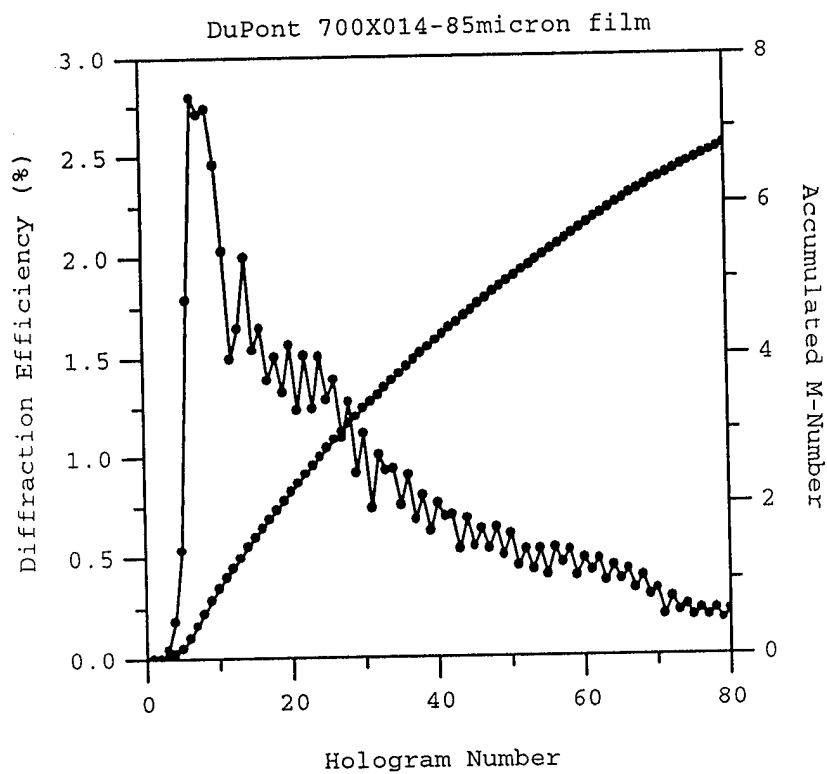


Figure 7. $M/\#$ characterization of a 85 μm thick film.

APPENDIX

```
DECLARE SUB shuttermachine (shcmd%)
DECLARE SUB resetmotors ()
DECLARE SUB resetsystem ()
DECLARE SUB chkpos ()
DECLARE SUB initdisplay ()
DECLARE SUB inputvariables (xinc!, yinc!)
DECLARE SUB motorhome ()
DECLARE SUB display ()
DECLARE SUB initialization ()
DECLARE SUB initiatemotor ()
DECLARE SUB motorx (xinc!)
DECLARE SUB motory (yinc!)
DECLARE SUB setmotor (cmd%, clr%)
DECLARE SUB movemotor (id%, nsteps%)
COMMON SHARED addr%, state%, f%, xpos, ypos, xxpos, yypos
COMMON SHARED shutterport%
```

```
CALL initialization      ' all parameters are set in this subroutine
CALL inputvariables(xinc, yinc)
```

```
CALL motorx(xinc)
CALL motory(yinc)
```

```
CALL motorhome
CALL resetsystem
```

```
END
```

```
SUB chkpos
```

```
IF xxpos > 44.3 OR xxpos < 0 THEN LOCATE 13, 5: PRINT xxpos; "mm out of x-axis range !!!!!!!"; :
STOP
IF yypos > 44.3 OR yypos < 0 THEN LOCATE 13, 5: PRINT yypos; "mm out of y-axis range !!!!!!!"; :
STOP
```

```
END SUB
```

```
SUB display
'COMMON addr%, state%, f%, xpos, ypos
```

```
LOCATE 21, 10
PRINT USING "###.#"; xpos
LOCATE 21, 30
PRINT USING "###.#"; ypos
```

```
END SUB
```

```
SUB initdisplay
'COMMON addr%, state%, f%, xpos, ypos
```

```
LOCATE 21, 5
PRINT "x = ";
LOCATE 21, 25
PRINT "y = ";
CALL display
```

```
END SUB
```

```
SUB initialization
'COMMON addr%, state%, f%, xpos, ypos
CLS
CALL initiatemotor
CALL initdisplay
```

```
END SUB
```

```
SUB initiatemotor
' addr%, state%, f%, xpos, ypos
```

```
xpos = 0: ypos = 0
state% = 0
addr% = &H378
OUT addr%, state%
f% = 4          'stepper speed = 200 steps/sec
```

```
END SUB
```

```
SUB inputvariables (xinc, yinc)
```

```
LOCATE 1, 10
PRINT "x increment (default = 0mm) >> ";
INPUT "", xinc: 'if xinc=0 then xinc=1
LOCATE 2, 10
PRINT "y increment (default = 0mm) >> ";
INPUT "", yinc: 'if yinc=0 then yinc=1
LOCATE 3, 10
PRINT "delay to start (default = 0sec) >> ";
INPUT "", delay: ' if delay=0 then delay=1
SLEEP delay
```

```
END SUB
```

```
SUB motorhome
'COMMON addr%, state%, f%, xpos, ypos
```

```
xinc = -xpos: yinc = -ypos
CALL motorx(xinc)
CALL motory(yinc)
```

END SUB

SUB motorx (xinc)

'common addr%, state%, f%, xpos, ypos

xxpos = xpos + xinc: CALL chkpos

id% = 1: dir% = 2 'clock#1

clr% = 255 - dir% ' CCW:bit 2 low

IF SGN(xinc) = 1 THEN dir% = 0 '+ve = CCW, -ve = CW

CALL setmotor(dir%, clr%)

nsteps% = INT(ABS(xinc) * 158)

CALL movemotor(id%, nsteps%)

xpos = xpos + xinc

CALL display

END SUB

SUB motory (yinc)

'common addr%, state%, f%, xpos, ypos

yypos = ypos + yinc: CALL chkpos

id% = 4: dir% = 8 'clock#2

clr% = 255 - dir% ' CCW : bit 8 low

IF SGN(yinc) = 1 THEN dir% = 0 '+ve = CCW, -ve = CW

CALL setmotor(dir%, clr%)

nsteps% = INT(ABS(yinc) * 158)

CALL movemotor(id%, nsteps%)

ypos = ypos + yinc

CALL display

END SUB

SUB movemotor (id%, nsteps%)

'common addr%, state%, f%, xpos, ypos

idlow% = 255 - id%

FOR i = 1 TO nsteps%

OUT addr%, state% OR id%

OUT addr%, state% AND idlow%

FOR j = 1 TO f%

NEXT j

NEXT i

END SUB

SUB resetmotors

cmd% = &H40: clr% = 255 - cmd%

CALL setmotor(cmd%, clr%)

cmd% = &H80: clr% = 255 - cmd%

CALL setmotor(cmd%, clr%)

END SUB

SUB resetsystem

CALL resetmotors

END SUB

SUB setmotor (cmd%, clr%)

'common addr%, state%, f%, xpos, ypos

' clr% = 255 - cmd%

state% = state% AND clr%

'clear memory of the bit to set

state% = state% OR cmd%

' set bit

OUT addr%, state%

END SUB

SUB shutter (shutterid%, action%)

IF shutterid% = 1 AND action% = 1 THEN shcmd% = 0

IF shutterid% = 1 AND action% = 0 THEN shcmd% = 0

IF shutterid% = 3 AND action% = 1 THEN shcmd% = 0

IF shutterid% = 3 AND action% = 0 THEN shcmd% = 0

CALL shuttermachine(shcmd%)

END SUB

SUB shuttermachine (shcmd%)

shstatus% = INP(shutterport%)

OUT shutterport%, shcmd%

END SUB